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Highway Viaduct Renovation

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Summary

The viaduct is positioned on the highway, connecting the city of Sofia with the northern part of Bulgaria. The total length of the viaduct is 645m, where it has 16 spans of 40.5m length each. The maximum height of the piers is 50m.
During the renovation of the deck and the piers has been discovered that some of the 120t post-tensioned concrete beams are in very bad condition. Approximately more than 50% from their origin load bearing capacity has been diminished. A decision was taken for these beams to be replaced by steel ones.
In the paper are described the design and the implementation of the renovation of the important structural elements, including the problems which were encountered upon. The design approach of the different elements has also been analyzed. The main innovation in the project is in the usage of concrete and steel beams in one and the same span. Due to the replacement of some post-tensioned beams with steel beams, the beneficent requested a full-scale load test of the bridge to be provided before it enters in operation again. The results from the static and dynamic tests of the renovated viaduct have been provided.
The renovated viaduct is in operation since the beginning of December 2015.

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Keywords: existing highway viaduct; renovation

1. Introduction

Approximately 120 kilometers of the existing highways in Bulgaria, through the mountains in both directions - south and north from Sofia, have been constructed between the years 1975 and 1988. In this area have been executed many viaducts as well with height reaching up to 130 meters. For the construction of these superstructures have been used three types of precast post-tensioned concrete beams - 27m, 39m and 58m in length. The heights of

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these beams are 180cm, 240cm and 330cm, while the weight is around 40t, 120t and 240t respectively. As a rule, the beams have been produced in a region very close to the erected viaducts and have been transported with special equipment at a very low speed. The beams were fixed on their positions by special steel truss structure with appropriate mechanical equipment. The concrete deck slab is cast-in-situ for the main number of these viaducts.

The concrete piers are with hollow core cross sections and were erected by using sliding formwork.

A special assessment made on the bridges along the highways and main roads in Bulgaria, that took place between 2004 and 2005 and was financed by the EU, indicated that the bridges are not in good condition. Moreover, according to the report from this investigation, 64 bridges are close to possible accident. There are many reasons for that, but the main one is connected with their improper design, construction and lack of maintenance.

The viaducts mentioned above mainly have problems with the piers, the continuous slabs, the expansion joints, the bearings, the drainage system, the carriageway surface, the surface of the pedestrian parts and the traffic-safety barriers. From structural point of view, the major problems are the damages to the piers and the continuous slabs. The defects in the drainage systems and the expansion joints are the reasons of the defects in the substructures - the continuous slab, the main beams and the bridge slab. The origin of some defects is due to the design concept problems in that type of structure.

The viaduct described in this paper has many problems including structure of the bridge deck slab, main beams and pier. The bridge renovation started in the spring of 2015.

The authors of this paper are part of the team under the leadership of Prof. Topurov, which preceded the investigation, design and full-scale testing of the renovated viaduct. The viaduct is in operation from the beginning of December 2015.

2. Original design

The viaduct has multi-span, simply supported superstructure. Each span is 40.5m long and there are 16 spans in number, so the total length of the bridge is approximately 650m. The beams in longitudinal direction are connected with continuous slab laid over the piers. The viaduct is divided in longitudinal direction in three parts with four expansion joints - two on the abutments and two in-between the ends. Intermediate expansion joints are allocated on the piers №5 and №11 respectively. The expansion joints are of a modular type. The superstructure is constructed with four precast post-tensioned beams, 39m long and around 120t in weight. The beams span is 38m. The deck slab is executed from precast element with 299cm by 305cm in size and 20cm thickness in cross direction. The connection between the precast panels is done with cast-in-situ concrete on top of the precast beams with suitable reinforced detail. This cast-in-situ joint combines the slab with the precast beams and the precast slab elements (see fig 1a). The superstructure has two cross beams at the end of each span. No intermediate cross beams are used.

Fig. 1 Longitudinal view of the viaduct

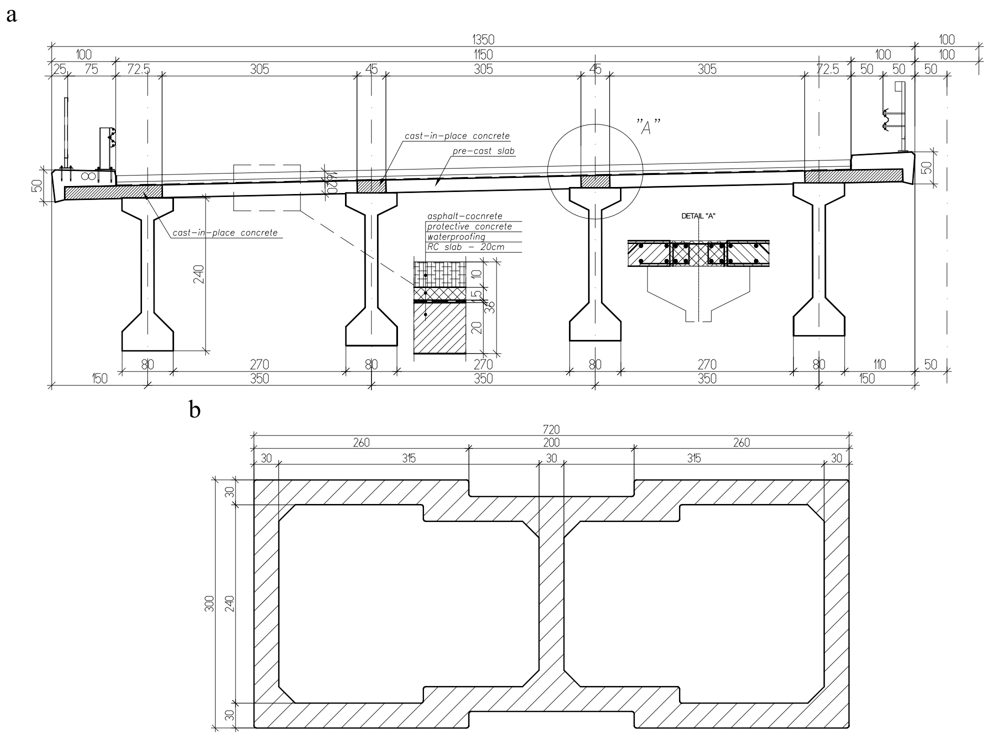

Fig. 2 Original design of viaduct: (a) cross section of the superstructure; (b) cross section of the pier.

The piers are with hollow core cross section (see Fig.2b) and their height reaches around 50m. They are supported by a shallow foundation. On top of the piers are constructed two cantilever cab beams on which are disposed the bearings. Two types of bearings are used - laminated rubber bearings and rolled steel bearings. The steel bearings are situated only on the expansion joints. The abutments are cast-in-situ cantilever structure.

The structure has been designed according to the Bulgarian code for road concrete bridges on the basis of the allowable stresses at this time [1].

The post-tensioned beams have been designed according to the German code DIN 4227 [2], because the Bulgarian code that was active at the time of design was not covering the design of the pre-stressed structures. The beam consists 19 cables with 12 strands of 7 mm diameter each. The controlled restressed force in each cable is around 50t. At that time, the designers the designers applied full pre-stressing, according to which after all characteristics loads (including the traffic load), the stresses in the tension zone remains positive.

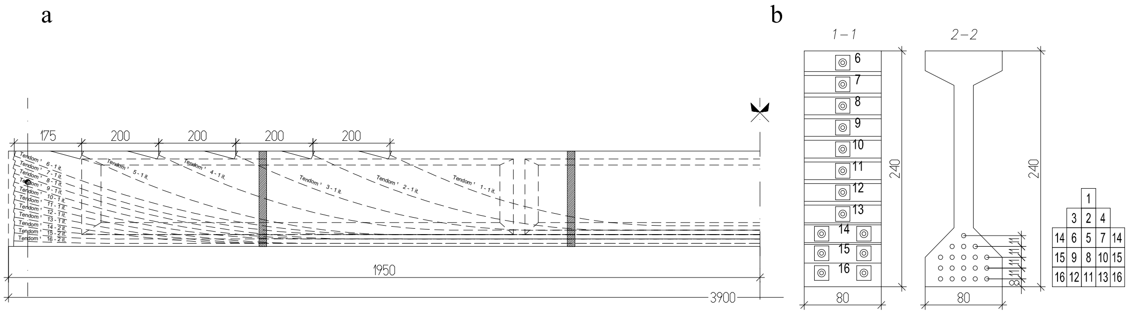

Fig. 3 View of post tensioned cables: (a) in longitudinal direction; (b) in cross section.

3. Defects description and analysis of the reasons

The main defects, which raised the need of an urgent renovation of the viaduct, were the punching of the deck slab at some places. The traffic was interrupted and a road assessment was initiated through complete investigation of the structure of the bridge. The investigation made revealed the main defects as follows:

3.1. On the deck slab

- Complete destruction of the concrete at some places;
- Completely destroyed bond between the concrete and the reinforcement at the lower surface;
- Concrete corrosion at the lower surface of the slab and partially exposed reinforcement due to water leakages through the slab or between the slab and the precast beams.

3.2. On the main beam

- Concrete and reinforcement corrosion at the side of the beam due to water leakages between the slab and the precast beam and through the pipe of the draining system. For some of the beams, more than 50% of the pos-tensioned cables, the concrete and reinforcement (stirrups and longitudinal) of the web are heavily affected by these leakages;
- Interrupted concrete cover in some parts due to the reinforcement corrosion;
- In some places the concrete cover exists, but the investigation has shown that there is no bond between the concrete cover and the main concrete of the beam (especially on the web).

3.3. On the cap beams

- Concrete and reinforcement corrosion due to water leakages through the expansion joints, especially at pier 11.

3.4. On the body of the columns

- In many places along the piers surface is visible concrete and reinforcement corrosion;
- In some places the concrete cover exists, but the assessment has shown that there is no bond between the concrete cover and the main concrete of the piers;
- In the base of some piers in their hollow section water was detected.

The viaduct has undergone some partial repairs while the structure was in operation. The last one was approximately 10 years ago. Some of the main beams and the deck slab were repaired with shot concrete that covered the damaged local places. This created some difficulties during the investigation, as the quality of the structural element under the shot concrete was undefined. The removal of this concrete was complicate. Several beams with huge affected surface were suspected to be in very bad condition, and decision was taken for their investigation to continue after the start of the bridge renovation.

The removal of the shot concrete during the construction phase has shown that the beams really are in severe condition. This was especially valid for some beams, where the inlets of the draining system were allocated, thus around 9 post-tensioned cables out of 19 were damaged. The steel sheet ducts, covered with lead, are fully destroyed by corrosion and more than 50% of the wires in the cables are affected by the corrosion as well.

The web concrete (approximately 50% of its thickness), stirrups and longitudinal reinforcement are destroyed by corrosion. The steel roller bearings need to be cleaned of the rust and grease, however the reinforcing elastomer bearings are in good condition.

Fig. 4 View of the post-tensioned cables

The pavement of the carriageway, the service sidewalks, the traffic barriers, the guard-rails and the expansion joints need to be completely replaced.

On the grounds of the investigation on the site, some calculations and appropriate analysis a report for assessment was summarized. According to it the main reasons for the defects are as follow:

- The thickness of the precast elements of the deck slab is not enough to ensure the strength of the structure and especially the shear force taking into consideration that the slab is directly loaded from the traffic. These precast elements further take part in the load distribution effects due to the missing intermediate cross beams;
- The precast elements of the deck slab were not properly placed on the precast beams. In addition, the concrete was not well vibrated in some places. Thus, the defective waterproofing allows the aggressive water to penetrate in the cast-in-situ joint causing defects on the slab and the beams;
- The inadequately constructed details and the lack of maintenance of the draining system lead to defects on the surface of the beams;
- The leakages through the defected expansion joints induces corrosion of the cap beam and the piers;
- The insufficient concrete coverage on the piers surface, combined with the inaccurate construction, the atmospheric influence and the defected draining system, caused moderate corrosion on the concrete and the reinforcement;

4. Design and construction of the renovation

The main requirement towards the design and construction of the renovation was associated with the terms. The construction started in the beginning of May, parallel with the assessment and the design. The target was all construction works to finish not later then the end of November.

On the base of the assessment results concerning the deck slab a decision was taken not only to restore the original strength, but to be retrofit it according to EN BDS 1992 [3] using the Eurocodes traffic load model. This lead to three different approaches concerning the slab renovation:

- At those places with destructed concrete or/and partially missing bond between the exposed bottom reinforcement and the concrete, the existing slab has to be removed using suitable equipment. For the casting of the new slab is to be used corrugated steel sheet as formwork. In these places the deck slab was design as ribbed slab with 30cm of thickness;
- At places with no destructed concrete and height corrosion of the exposed bottom reinforcement after the sand blasting of the surface is applied shot concrete, and these places are then strengthened with carbon fibre in the epoxy matrix. In addition, 10cm structural concrete with relevant top reinforcement is applied, aiming an increase in the strength of the deck slab according to EN BDS 1992 [3].
- In case the concrete surface is in a good condition, or the exposed bottom reinforcement is with small corrosion, the reinforcement was treated suitable and again it was designed with a 10cm structural concrete.

In order not to increase the dead load, although the deck thickness was changed, with permission of the National Road Authorities the thickness of the asphalt was reduced from 10cm to 8cm and the 4cm protection waterproofing concrete was not provided. In addition, the 2cm concrete under the waterproofing was removed under the premise that it will be executed with suitable surface. In fact, the increasing of the dead load is with 2cm concrete thickness which is negligible, but this was taken in to consideration for the verification of the main beam girders.

For the repair of the main post-tension precast beams were discussed three possible variants:

- Strengthening by using carbon fibres for the bending moment and for the shear forces;
- External pre-stressing for the bending moment and carbon fibres for the shear forces;
- Concrete beams to be replaced by new concrete precast beams;
- Concrete beams to be replaced by steel beams.

The study of the first option pointed problems in the montage of the carbon fibers, because the surface of the bottom flange of the beams was in very bad condition and was difficult to be shaped with shut concrete. The option to do the repair by using carbon fiber textile which is sensitive for fixing any surface was considered very expensive. In addition, there is a problem for strengthening using carbon textile for shear force, especially for principle compression stress.

The second option was problematic as well in the part of the shear force strengthening. In addition, the external pre-stressing was new technology for the contractor and due to the small quantity of work the offer from Freyssinet was considered very expensive. For financial and time conditions, this option was abandoned as well.

The third option proved revealed that the transportation and fixing on the spot of the 39m concrete beam with minimum weight of 80t is very complicated. For this reason, this option was also abandoned.

The designer decision was to replace the concrete beams with steel ones. The measurement of the steel beam was chosen to have the same height as the concrete one due to be fixed at the same position, so that the existing bearings can be used as well. The other measurements (thickness of the plate and width of the flanges) were chosen at the base of the equal stiffness. Furthermore, for the dynamic response related with traffic action it was important that the mass is not significantly different. The steel beams should be allocated on the edge of the deck where the additional permanent mass from the sidewalk were placed (see fig 5).

a b

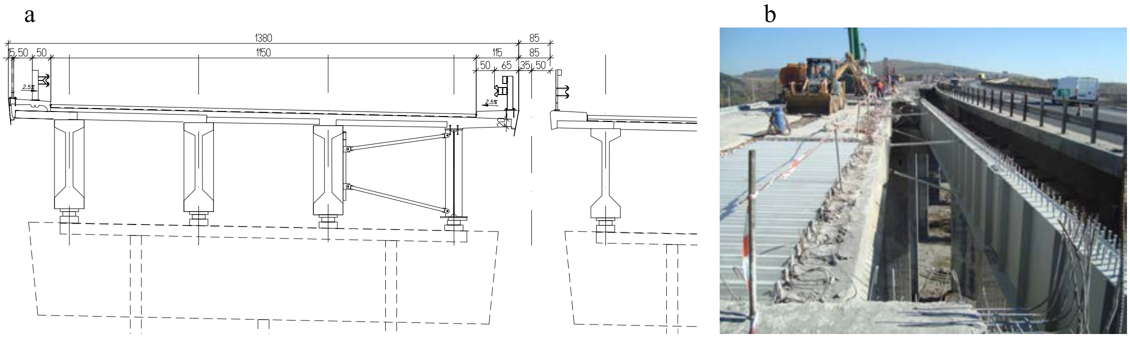

Fig. 5 Steel beam: (a) cross section of deck with allocation of steel beam; (b) longitudinal view of steel beam.

Due to the easy production and transportation the 39m long steel beam was designed into three parts connected by friction joint at the places where the bending moment is small.

The main difficulty was the dismantling of the 110t heavy concrete beams at a height of about 30m. This was made with two heavy duty mobile cranes allocated from both sides on the span (see fig 6). The other difficulty came from the distance between the cap beam of the neighboring (parallel) viaduct (see fig 5b).

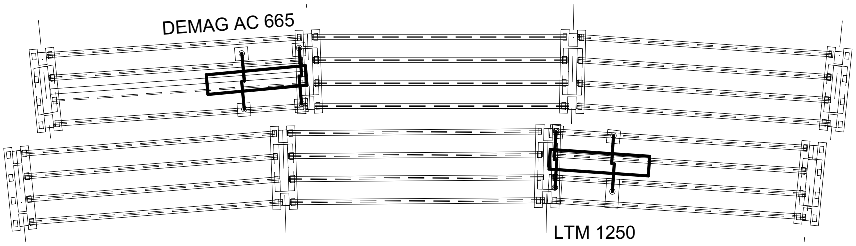

Fig. 6 Scheme for allocation of the mobile cranes

The replacement of the beams was in the following sequence:

- Dismantling of the deck slab between the concrete beams. A 3m strip was left for stability;
- Allocation of the cranes in foresee position and hooking of the concrete beam;
- Dismantling of the remaining strip of the slab;
- The cranes lifting the beam slowly and carefully dropping it on the terrain under the bridge;
- Lifting of the steel beam from the ground and fixing it on the bearings. Fixing using braces against buckling of the steel beam during the casting of the new deck slab;
- Unhooking of the beam by the cranes.

During the work of the cranes, the traffic in the other highway carriageway was stopped completely for 2 hours.

The main defects on the piers and cap beams were in the exposed and slightly corrugated reinforcement and/or the lack of bonding between the concrete coverage of the reinforcement and the basic concrete. The main repairing works for the piers and cap beams were done in the following sequence:

- Large unbounded pieces of concrete coverage were removed mechanically, after which sand blasting was applied;
- Steel mesh 5cm by 5cm with 5mm bar diameter were fixed to the concrete by anchors;
- Concrete coverage from of about 5cm was created by applying shot concrete on top of the mesh.

In some piers these defects were to be seen in huge areas on the surface. The bottom part (at about 10m height from the ground) at pier №11 was in very poor condition. That's why a strengthening with carbon fiber sheets was designed.

All functional elements as water-proofing, pavements, sidewalks, expansion joints, traffic barriers and parapets were completely replaced with new ones.

5. Full-scale test and results

According to the relevant decrees for this type of bridges, in order for the bridge to be put in operation again, no tests were necessary to be made after the finishing of the construction works. In this special case however, the National Agency "Road Infrastructure" required full-scale test to be implemented so that the response of the structure under the static and dynamic loads to be checked. A decision was taken for static test of four spans from the renovated structure of the bridge and dynamic test of two spans, chosen according to the following reasons:

Span 1- deck slab without strengthening except the 10cm additional top reinforced concrete, marginal repairing of one beam with carbon fibers.

Spans 4, 5 and 6- steel beams, partially ribbed deck slab, different slab repairing works including carbon fibers.

During the test were used 44t heavy duty tracks (see Fig. 7). The tracks were allocated close to the side where the steel beams are located. The deflections in the middle of each beam were measured in two stages by the static test.

For the dynamic truck test on the pavement at the beginning of each span was situated a threshold of 5cm thick wooden plank. The first test was made without the wooden plank due to the estimated dynamic amplification of the stresses. Then several other tests were made during which the truck passed through the wooden plank at different speed, causing dynamic excitation. Due to these tests the superstructure started to vibrate intensively. The amplitude and the accelerations of the superstructure vibration were measured and recorded by means of special equipment. For each span the sensors of the equipment were allocated at the sidewalks and under the middle beam.

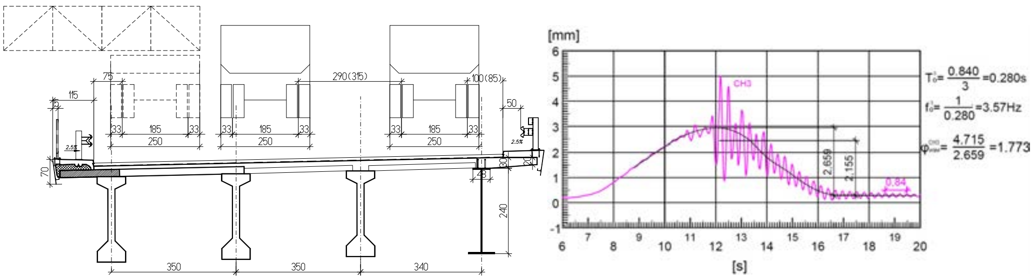

Fig. 7 Testing the renovated viaduct: (a) cross section of the carriageway with allocation of tested tracks- load case 2; (b) graphics recorder with equipment „QUANTUM" from dynamic test in span 1.

Numerical 3D model was created for making a comparison between the testing results and the theoretical results, by applying only shell finite elements for SAP2000 V16.0.2. The minor damping properties of the laminated elastomeric bearings were not taken into consideration in the model.

The results from the static test showed good response of the structure. The variation between the theoretical and practical test results (average 25%) can be explained in the following way:

- Undetermined estimation of the module of elasticity of the concrete, only the results at the steel beam (P8) came with small deviation;
- Other factors include correct modeling of the track position, not good modeling of the concrete on the sidewalks, etc.

It is important to be pointed out that in reality the structure has higher stiffness compared to the theoretical model. The test results further made it obvious that the load distribution at the cross direction of the two spans is comparable.

The Eigen frequency (for first vertical mode) defined from the dynamic test in span 1 and 4 is almost the same - between 3,55Hz and 3,98Hz, average - 3,67Hz. This shows that the span with steel beam has similar response like the one with four concrete beams. The theoretical calculation of the Eigen frequency for the first vertical mode is respectively:

f_0=3,56Hz – span 1 and f_0=3,50Hz –span4.

From passing the track without threshold the dynamic amplification defined from the records is calculated to be 1,016Hz. This very good dynamic amplification can be explained by the fact that the asphalt pavement is new and very smooth.

6. Conclusion

Taking into consideration the result from the viaduct defects assessment, it became clear that the bad maintenance leads to huge losses due to the need for repairs of the bridge's usability (from safety and functionality points of view). In addition, the improper design using precast elements for relatively thin deck slab generates defects which can cause an accident. When the deck slab in girder superstructure has no intermediate cross beam, it is extra loaded by the spatial distribution of the traffic action. In the original design this probability was not properly taken into consideration. The designed joint detail at the connection between the precast slab elements and the precast beams is not suitable for this superstructure.

The increase of the deck slab thickness does not improve the strength of the slab, but changes the way in which the loads are spatially distributed.

References

[1] Temporary regulations for design of concrete and reinforced concrete bridges. 1973
[2] DIN 4227 Prestressed concrete - Part 1: Structural members made of normal-weight concrete, with limited concrete tensile stresses or without concrete tensile stresses
[3] BDS EN 1992-2 Eurocode 2: Design of concrete structures - Part 2: Concrete bridges - Design and detailing rules